

Photon Pickup by Intense Poynting Flows

David Eichler¹

¹*Physics Department, Ben-Gurion University, Beer-Sheva*

It is suggested that a Poynting flux-dominated outflow with a sufficiently strong magnetic field can pick up hard X-ray photons when the magnetic field is of sufficient strength. The zeroth generation X-rays pair produce, and the pairs radiate extremely energetic first generation photons that could be detected by extensive air shower arrays and/or MILAGRO if they escape the production site intact. Giant flares from magnetars may thus yield bursts of UHE photons. GRB-associated Poynting flows may be unstable to pair production near their source, and their energy rapidly converted to pairs.

PACS numbers:

INTRODUCTION

There is growing evidence that soft gamma ray repeaters (SGR's) and anomalous X-ray pulsars are objects with ultrastrong magnetic fields, $10^{14.5}$ G or more [1, 2, 3]. Giant flares from SGR's appear to be caused by a reconnection or reconfiguration of an ultrastrong magnetic field, in a manner similar to the mechanism that causes solar flares. These flares have two stages: a) the bright phase, lasting $\sim 10^{-1}$ s, when the energy is presumably released, b) a period lasting several minutes during which time the remaining plasma is apparently trapped on closed field lines. More than 10^{44} ergs may be released in giant flares, while smaller, more frequent bursts field between 10^{38} and 10^{42} ergs.

A rapidly rotating neutron star with a magnetic field of at least 3×10^{14} G was proposed by Usov [4] as being the source of gamma ray bursts (GRB's). One indication (of sorts) is that synchrotron models of afterglow frequently invoke a rather large fraction of the total fireball energy in Poynting flux to obtain good fits (e.g. [5]). Other models [6, 7] explicitly invoke Poynting flux as being the original form in which GRB energy is expelled by the compact object. The rate at which magnetars form can be estimated by dividing the number in the Galaxy (~ 10) by their age ($\sim 10^4$ yr), and the rate so estimated, once per $\sim 10^3$ years per galaxy, is consistent with what is needed to produce GRB's. Perhaps magnetars are the fossil remnants of GRB's.

It would be useful to identify a qualitative consequence of ultrastrong magnetic fields, one that would not exist to any degree were the fields much smaller. In this letter, it is suggested that pair production by photons in a magnetic field could be just such a consequence and could result in the emission of ultrahigh energy (UHE) photons. The basic point is that such coupling is possible in a magnetic field only when the product of the photon energy ϵ_γ and field strength B_\perp normal to the photon path satisfies

$$\epsilon_\gamma B_\perp \geq 2 \times 10^{18} \text{ eV} - G. \quad (1)$$

Thus, when the field strength exceeds 10^{14} G, a photon above 20 KeV (routine for typical astrophysical thermal X-ray emitters) suffices. (Hereafter the subscript in B_\perp will be dropped.)

We will assume in this letter without rigorous proof that, in a flare-like event, plasma can be ejected from a magnetar or similar object to infinity, much like plasma is ejected from the Sun by solar flares, but with a very large Lorentz factor ($\Gamma \geq 10^4$) characteristic of the large Alfvén Lorentz factor associated with tenuous plasma in a strong magnetic field. At this Γ , the plasma moves essentially at the speed of light, to within one part in 10^8 . There is little relative motion between the photon and the plasma over a hydrodynamic timescale, which, in the frame of the fluid, is much shorter than the crossing time measured in the lab frame.

BASIC CONSIDERATIONS

Consider a strongly magnetized compact object (SMCO), e.g. neutron star, collapsar or accreting black hole of radius R , with a field strength B , $B \gg B_{QED} \equiv 4.4 \times 10^{13}$ G. Because the gravitational field allows a negligible thermal scale height, the plasma density well above the surface is determined purely by electrodynamics, and is of order $B/4\pi R\beta$, where βc is the velocity of the charge carriers. The characteristic current density associated with the field is of order $cB/4\pi R$, and the minimum proton or electron number density associated with this charge density, $n = j/e\beta c$, is $n \sim B/4\pi R e \beta c \sim 2 \times 10^{17} B_{15} R_6 / \beta \text{ cm}^{-3}$ where numerical subscripts of any quantity refer to powers of ten by which the quantity is to be multiplied when expressed in cgs units. If the current is carried by protons, then the energy per current-carrying proton, $B^2/8\pi n$, is of the order of

$$\sigma m_p c^2 \equiv eBR = 10^{14.5} B_{15} R_6 m_p c^2. \quad (2)$$

For a magnetar, the energy per current-carrying proton can be as high as $10^{14.5} m_p c^2$. If an overweight, "failed" or spun-down magnetar collapses to a black hole [8], then, just prior to completing this collapse, it would have a field of about an order of magnitude higher, and $\sigma \sim 10^{15}$. (In practice, a single species plasma would result in extremely high electric fields and the plasma is likely to be quasi-neutral. In this case, the multiplicity ξ , i.e. the ratio of the actual plasma mass density to the minimum needed to provide the curl of \mathbf{B} , is likely to be greater than unity. In pulsars, the charge multiplicity is unknown, but could be as high as 10^4 or more [9], and if, as will be assumed here, the current carriers include ions, the mass multiplicity is even less certain.) If a significant fraction of this magnetic energy density is stored in a solenoidal component of this field, it could be released by reconnection and current dissipation.

To simplify geometric considerations, consider a uniform magnetic field $\mathbf{B} = 10^{15} B_{15} \mathbf{b} \text{G}$, where \mathbf{b} is the unit vector in the field direction, and a frame that moves perpendicular to \mathbf{B} with Lorentz factor Γ relative to the frame of the compact object, hereafter called the lab frame. In the zero electric field frame (ZEFF), the magnetic field strength is

$$B' = B/\Gamma. \quad (3)$$

This basic fact is used repeatedly below. The Lorentz factor of the particle in the ZEFF will be denoted by γ' . Note that criterion (1) is not only Lorentz invariant, as could be expected intuitively, but also, in light of equation (3), independent of Γ to within geometric factors. Ultrarelativistic motion of the plasma, while lowering B' relative to B , raises $\epsilon'^{(o)}$ relative to $\epsilon^{(o)}$, the lab frame energy of the incident photon, by about the same factor.

Another necessary condition for pair production is that the photon energy in the ZEFF exceed $2m_e c^2$. Photons this energetic are not typically emitted by thermal processes in astrophysical situations. However, if the ZEFF is sufficiently ultrarelativistic in the frame of the photon source, this is not a problem for X-rays, for then the photon as seen in the frame of the plasma is Doppler-boosted well above the pair production threshold.

PHOTON PICK-UP

A photon with lab frame energy E_{ph} has an energy in the frame of the piston of $E'_{ph} = E_{ph}\Gamma$ to within a geometric factor. Photons satisfying $E'_{ph}B' \geq 2 \times 10^{18} \text{ eV-Gauss}$ are converted to pairs. The pairs emit synchrotron radiation at a frequency of $2 \times 10^7 \gamma'^2 B'_0$ in the local comoving frame where B'_0 is the ZEFF field strength in Gauss. As they slow down, they emit an increasing number of photons per decrease in $\ln \gamma'$. Assuming that the pair has a pitch angle of 90 degrees, then, in the classical approximation,

$$d\gamma'/dt' = -2\gamma'^2 \sigma_T B'^2 / 8\pi m_e c \quad (4)$$

and

$$d\theta'/dt' = eB'/\gamma' m_e c. \quad (5)$$

Choosing $\theta = 0$ to be the starting direction of the pair, i.e. opposite to the direction of the plasma, and assuming the initial γ' to be very large, we can write the solution to equations (4) and (5) as

$$\gamma' = \left(\frac{3c}{4r_o \omega'_c \theta'} \right)^{1/2}. \quad (6)$$

The characteristic energy of the emitted photons ϵ' is given by

$$\epsilon' = \frac{3c\hbar}{4r_o \theta'}. \quad (7)$$

The lab frame energy ϵ is given by

$$\epsilon = \Gamma(1 - \beta \cos\theta')\epsilon'. \quad (8)$$

The spectrum of emitted photons as seen in the lab frame is easily calculated by noting that the rate of photon emission per unit proper time in the plasma frame is constant:

$$dN/dt' = R \quad (9)$$

where N is the cumulative number of photons that have been emitted and $R \sim \sigma_T c(B'^2/8\pi\hbar\omega_c')$, and

$$N = A\theta'^{1/2} \quad (10)$$

where $A = \frac{2R}{\omega_c} \left(\frac{3c}{4r_o\omega_c} \right)^{1/2}$.

Writing the total energy spectrum in the lab frame is complicated by the fact that (7) and (10) combine to form a transcendental, non-monotonic relation between N and ϵ . However, it is easy to write ϵ as a function of N by using (10) and (7 in (8)):

$$\epsilon = \frac{3\hbar c}{4r_o} \Gamma [1 - \beta \cos([N/A]^2)]/[N/A]^2. \quad (11)$$

The solution can then be "turned on its side" to obtain $dN/d\epsilon \equiv \sum(dN/d\theta')/(d\epsilon/d\theta')$ by summing the contributions of the individual segments for which N is monotonic in ϵ . From here on, β will be taken to be essentially unity. In figure 1, the individual components of the spectrum are plotted for the first 10 gyrations, gyration by gyration, in the delta function approximation [see eq. (7)]. The total spectrum at most energies (not shown) is dominated by the individual peaks and appears quite similar to the graph in the figure.

At low energy, the spectrum is essentially

$$dN/d\epsilon \propto \epsilon^{-3/2} \quad (12)$$

which is a familiar result for the time-averaged emission of decelerating, energetic particles. At high energy, most of the energy in the first generation photons is emitted in a very narrow peak near

$$\epsilon^{(1)} = [1 - \cos(3\pi/4)]\Gamma m_e c^2 / \pi\alpha. \quad (13)$$

The lab frame energy is thus

$$\epsilon^{(1)} \sim 38\Gamma MeV \quad (14)$$

which, for the magnetosonic value of Γ , $\Gamma = (\sigma/\xi)^{1/2}$, can exceed $10^{15}(\sigma_{15}/\xi)^{1/2}$ eV. Note that the lab frame energy depends only on the Lorentz factor of the fluid element in which it is produced.

Photons this energetic survive in the high Γ outflow, which has a much lower field than the lab frame, provided that

$$\epsilon' B' \sim 38MeVB/\Gamma \leq 2 \times 10^{18}eV - G. \quad (15)$$

This is satisfied when $\Gamma \geq (B/5 \times 10^{10}\text{Gauss})$. For magnetar strength fields ($B \sim 5 \times 10^{14}\text{G}$), Γ must exceed 10^4 , and the surviving photon energies must therefore exceed 0.5 TeV. The velocity difference between the fluid element and the photon is exceedingly small, and they move together. If the fluid element is ejected to infinity from the magnetosphere, in analogy to fast streams from solar flares, then the photon moves with the host fluid element out to infinity, where the field is too weak for further pair production.

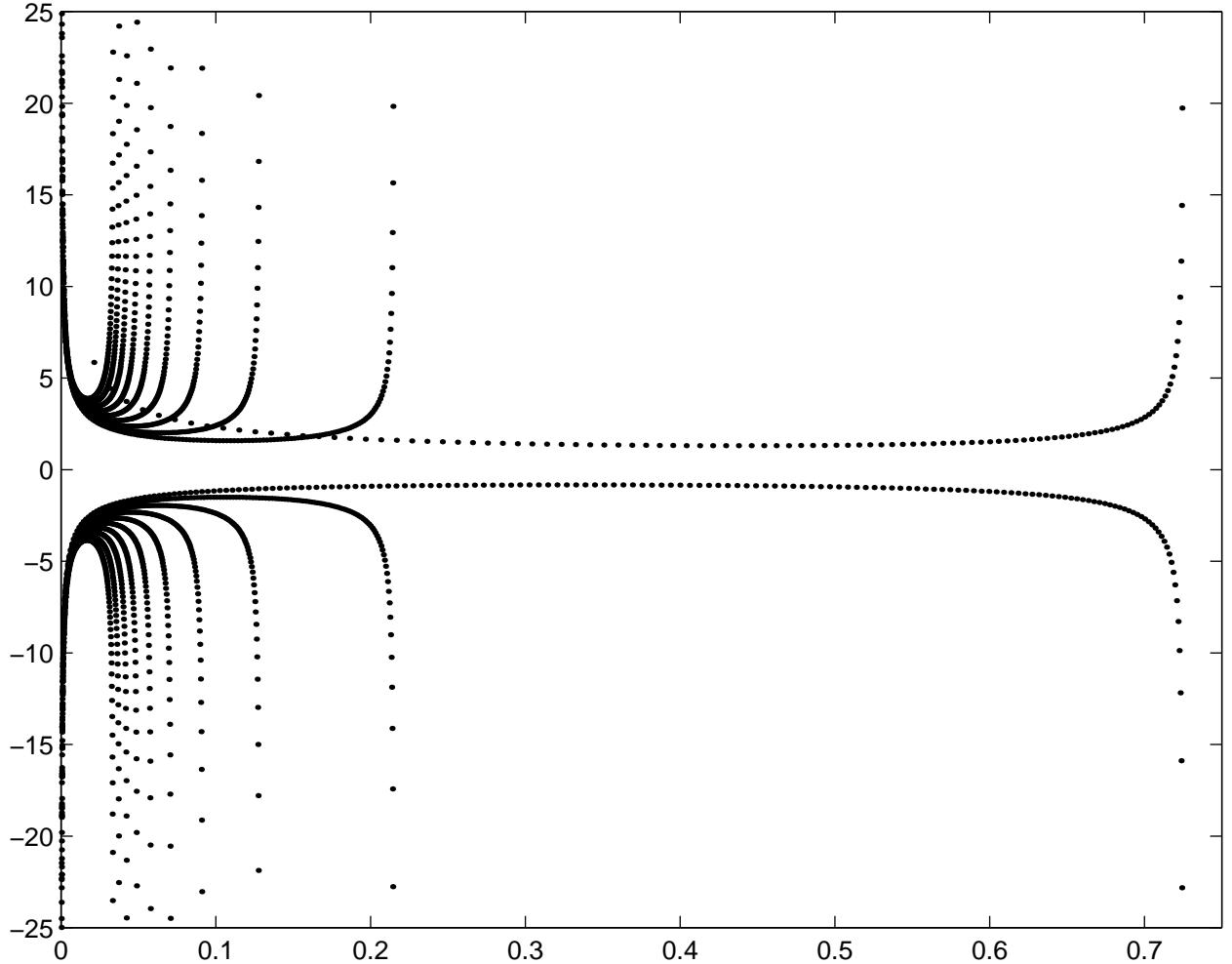


FIG. 1: The differential spectrum $dN/d\epsilon$ of gamma rays emitted by a pair that is produced by a picked-up photon. For simplicity, it has been assumed that the instantaneous spectrum is a delta function at energy ϵ' given by equation(7); the actual peaks would be somewhat broader. The pair begins moving in the backward direction ($\theta = 0$) relative to the motion of the fluid element. The lab frame energy of the emitted photons rises as the pair gyrates toward the forward direction, and, at $\theta^* = 2\pi n + 2.33 \sim 2\pi n + 3\pi/4$, begins to decline. To graphically separate the rises and declines, the spectral contributions from the declining phases are plotted as negative numbers, i.e. $-dN/d\epsilon$. The unit of energy on the x axis is $3\Gamma m_e c^2/4\alpha = 52.51\text{MeV}$. The interval between adjacent dots denotes 1.2° of gyrophase, 300 per gyration. The y axis is left arbitrary but the total number of emitted photons is easily estimated as $\gamma' m_e c^2/\epsilon'$. The divergence of $dN/d\epsilon$ at θ^* is due to the vanishing of $d\epsilon/dt$, but the total area under the peak is finite.

If, on the other hand, the photon is produced within a fluid element where equation (15) is not satisfied, the pair cascade continues. The second generation pairs would have ZEFF energy $\epsilon' \sim 3m_e c^2/2\pi\alpha$ and the second generation photons they emit would have a lab frame energy of

$$\epsilon^{(2)} = \left(\frac{3}{2\pi\alpha} \right)^2 \left(\frac{\Gamma B'}{B_{QED}} \right) m_e c^2. \quad (16)$$

In general, this is not enough to escape the thermal photon field of the compact object (see below), and a pair cascade should degrade the energy of the higher generation photons down to tens of MeV.

OBSERVATIONAL SIGNATURES

Let us now consider this mechanism in the context of flares from SGR's. Our approach is to recognize the complexity of magnetic field annihilation and merely assume without detailed argument that magnetospheric motion is generated with a Lorentz factor of about the Alfvén Lorentz factor $[B^2/(8\pi\rho_o)]^{1/2} \sim (\frac{\sigma}{\xi})^{1/2}$. The value of σ in a magnetar magnetosphere can exceed 10^{14} , hence the Alfvén Lorentz factor, $\sigma^{1/2}$, can exceed $\xi^{-1/2}10^7$. By equation (14), each of these first generation photons can result in $2N_\gamma$ photons emitted at near $38\sigma^{1/2}\xi^{-1/2}\text{MeV}$, where N_γ is given by

$$N_\gamma \sim [\gamma'(\theta')m_ec^2/\epsilon'(\theta')]_{\theta'=3\pi/4} \sim \alpha^{1/2}(B'/B_{QED})^{-1/2}. \quad (17)$$

A typical SGR has a persistent soft X-ray luminosity of order 10^{35} erg/s, implying a quiet time magnetospheric photon density of order 10^{21} photons/cm³. If each zeroth generation photon results in N_γ photons of 10^{15} eV, up to $10^{24}N_\gamma$ ergs/cm³ result in first generation photons. For reasonable parameters, this can dominate the flare energy (10^{25} erg/cm³ is a typical value for the latter in the case of large flares), implying that this mechanism may actually absorb most of the flare energy. We suggest that this allows for the possibility of flares that are quiet in soft gamma rays, while most of the energy is in the form of much more energetic photons.

The UHE photons must still contend with thermal X-ray photons from the magnetar surface, most of which pass easily through the magnetic field. Assuming, somewhat generously, that the X-radiation is half a black body photon field extending 5×10^5 cm, with temperature $kT=0.5$ KeV, then the $\gamma - \gamma$ opacity felt by UHE gamma rays, which goes as

$$\kappa_{\gamma,\gamma} = (\pi^2/3)\alpha^3r_o^{-1} \left(\frac{kT}{m_ec^2} \right)^3 \left(\frac{(m_ec^2)^2}{\epsilon kT} \right) \ln \left(0.117 \frac{(m_ec^2)^2}{\epsilon kT} \right) \quad (18)$$

[10], requires the photons to be above several TeV in energy in order to escape the thermal photons from the magnetar surface.

The photon energy for first generation photons of $\epsilon^{(1)} \sim 10^{15}$ eV is large enough to be detected as an extensive airshower, and could be detected with surface arrays. The naturally wide-angle fields of view of such detectors make them especially suitable for monitoring the sky for occasional bursts. Because outward expulsion of plasma is necessary to escort the photons through the otherwise high magnetic fields, we predict that UHE photons would emerge only during the initial hard spike of a giant flare, which lasts at most tenths of seconds, and is usually associated with an escaping pair plasma.

Similarly, MILAGRO could pick up bursts of photons above 1 TeV. It is worth emphasizing that bursts from magnetars are rare, the largest bursts occur only once per 20 years or so, and positive detections at these energies might therefore also be rare. In contrast to most GRB's, which are undetectable by MILAGRO due to attenuation by pair creation over cosmological distances, the occasional giant SGR flare, which is Galactic, could very well be detectable.

Finally, we consider the possibility of detecting similar bursts from nearby galaxies with MILAGRO. Making the best-case assumption (among the wide range allowed by the uncertainty in Γ) that the UHE photons emerge at $\sim 3\text{TeV}$, a burst of $\sim 10^{44}$ ergs would yield $\sim 10^{43.5}$ photons. If the detecting area is $10^4 A_4$ m², and assuming two or three simultaneous photons constitute a detection, then photons are detectable out to $\sim 3A_4^{1/2}$ Mpc. Thus it might be worthwhile to monitor for directional coincidences with nearby galaxies within this range.

GRB's: If GRB's originate from Poynting flows out of strongly magnetized compact objects (SMCO's), presumably rapidly rotating neutron stars or black holes, then, close to the SMCO, the field exceeds B_{QED} . We now argue that such a flow, if surrounded by hot plasma from an accretion, disk, corona, wind, or collapsing core of the host star, is subject to the above mechanism of photon pick-up and is unstable to

the formation of a fireball. Zeroth generation gamma rays of order $\epsilon^{(0)} \sim m_e c^2$ would be emitted by the surrounding plasma and any gamma ray produced within the Poynting outflow would have a good chance of scattering off the wall and back into the outflow, while retaining an energy of order $m_e c^2$. It would pair produce and emit more high energy gamma rays, which would also pair produce. As long as $B/B_{QED} \geq \Gamma \gg 1$, the electromagnetic energy can be converted to pair energy in several hydrodynamic crossing times. The scales at which this process takes place are less than 10^8 cm, and the compactness parameter is sufficiently high that most of the pairs would eventually annihilate. The final output would then be prompt gamma rays peaking at energies just below the pair production threshold, quite like the thermal component of GRB's. It would be hard to distinguish different scenarios (e.g. simple two-photon pair production) for converting Poynting flux to pair energy at the most compact scales of GRB's. In fact, other pair production mechanisms (e.g. $\gamma - \gamma$) could continue out to larger scales. We argue only that the strong magnetic field presents at least one scenario that triggers the conversion of Poynting flux to pair energy very early in the life of the GRB eruption.

To summarize, we have suggested a process for energetic photon emission that can happen only if $B \gg B_{QED}$. We suggest the possibility of extremely energetic photons from giant magnetar outbursts in the Galaxy, and perhaps nearby galaxies, which would be detectable with extensive air shower arrays. However, because significant disruption of the magnetosphere is necessary for such energetic photons to escape, the events should be rare within a single galaxy and their detectability may rely heavily on the persistent air time and large fields of view of extensive air shower array detectors. A characteristic signature of the mechanism would be a very hard spectrum with an abrupt high energy cutoff.

We note that extreme Poynting flux from GRB's can be converted to a pair fireball very close to the source by the same mechanism.

I gratefully acknowledge very helpful discussions with Y. Lyubarsky, and C. Thompson. This research was supported by an Adler Fellowship administered by the Israel Science Foundation, by the Arnow Chair of Astrophysics, and by the Israel-U.S. Binational Science Foundation.

- [1] Duncan, R.C. & Thompson, C., 1992, ApJ 408, 194
- [2] Thompson, C. & Duncan, R.C., 1993, ApJ 392L, 9
- [3] Woods, P.M., Kouveliotou, C., Gogus, E., Finger, M.H., Swank, J., Smith, D.A., Hurley, K., & Thompson, C., 2001, ApJ 552, 748, and references therein
- [4] Usov, V.V., 1992, Nature 357, 472U
- [5] Livio, M. & Waxman, E., 2000, ApJ 538, 187
- [6] Thompson, C., 1994, MNRAS 270, 480
- [7] Lyutikov, M., Parlev, V.I. & Blandford, R.D., 2003, astro-ph 0305410
- [8] Vietri, M. and Stella, L., 1998, ApJ 563, L45
- [9] Hibschman, J.A. & Arons, J., 2001, ApJ 560, 871
- [10] Gould, R.J. and Schreder, G.P., 1967, Phys. Rev. 155, 1404